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COMPARING THE PALMER DROUGHT INDEX AND THE STANDARDIZED PRECIPITATION INDEX[1]

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ABSTRACT: The Palmer Drought Index (PDI) is used as an indicator of drought severity, and a particular index value is often the signal to begin or discontinue elements of a drought contingency plan. The Standardized Precipitation Index (SPI) was recently developed to quantify a precipitation deficit for different time scales. It was designed to be an indicator of drought that recognizes the importance of time scales in the analysis of water availability and water use.

This study compares historical time series of the PDI with time series of the corresponding SPI through spectral analysis. Results show that the spectral characteristics of the PDI vary from site to site throughout the U.S., while those of the SPI do not vary from site to site. They also show that the PDI has a complex structure with an exceptionally long memory, while the SPI is an easily interpreted, simple moving average process.
(KEY TERMS: precipitation; drought; drought index; climatology; time series analysis.)

INTRODUCTION

The Palmer Drought Index (PDI) is used as an indicator of drought severity, and a particular index value is often the signal to begin or discontinue elements of a drought contingency plan. The index has been calculated on a regular basis for about 30 years as a means of providing a single measure of meteorological drought severity. It indicates the physical severity of a drought on soil, and is generally considered to be useful primarily for agricultural and other water uses that are sensitive to soil moisture.

The index was developed in 1965 (Palmer, 1965) and called the Palmer Drought Severity Index (PDSI). It was intended to retrospectively look at wet and dry conditions from a water balance viewpoint. Variations of the index include the modified PDSI, which is designed for real-time use, the Palmer Hydrologic Drought Index, which is used for water supply monitoring, and the Z Index, which is a measure of an individual month's wetness or dryness. The index and its variations have been used extensively for monitoring drought and for making operational water management decisions. Some of the properties and sensitivities of the PDSI and its variations have been investigated by Alley (1984), Heddinghaus and Sabol (1991), Karl (1983, 1986), Guttman (1991), and Guttman *et al.* (1992).

The PDSI and its variations were designed to be standardized so that index values would have comparable meaning at all locations and times. However, the referenced studies show that the intended assumption of standardization is, in reality, not valid. Spatial and temporal comparisons may therefore be misleading and lead to erroneous conclusions by users of the Palmer indices.

A new index, called the Standardized Precipitation Index (SPI), was developed by McKee *et al.* (1993, 1995) to give a better representation of wetness and dryness than the Palmer indices. In contrast to the Palmer indices, which are based on a monthly water balance accounting scheme that involves precipitation, evapotranspiration, runoff and soil moisture, the SPI was developed to quantify a precipitation deficit for different time scales. It was designed to be an indicator of drought that recognizes the importance of time scales in the analysis of water availability and water use. The SPI is essentially a standardizing transform of the probability of the observed precipitation. It can be computed for a precipitation total observed over any duration desired by a user (1-month SPI, 6-month SPI, etc); short term durations of

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the order of months may be important to agricultural interests while long term durations spanning years may be important to water supply management interests.

The SPI may be a better indicator of wetness and dryness than the Palmer indices. Despite their limitations and potential for misinterpretation, the Palmer indices have been used for monitoring and decision making for decades and are therefore very familiar to the user community. If the SPI is to replace the Palmer indices as a measure of drought and wet events, it will be necessary to compare the characteristics of both types of measures. This comparison is necessary so that users will be able to transfer their familiarity with and use of the Palmer indices to the SPI. This study compares the spectral characteristics of the SPI to those of the modified PDSI(PDI). This variation of the PDSI was chosen for comparison because it is routinely computed and published on a real-time basis.

PALMER DROUGHT INDEX (PDI)

The Palmer Drought Index was designed to quantify meteorological drought. Drought was considered to be a prolonged and abnormal moisture deficiency rather than an indicator of the effects of a prolonged weather anomaly. A drought period was defined as an interval of time, generally of the order of months or years in duration, during which the actual moisture supply at a given location consistently falls short of the climatically appropriate moisture supply. The severity of a drought was considered to be a function of both the magnitude and frequency of the moisture deficiency.

The index is calculated by first carrying out a hydrologic accounting by months for a long series of years. The results are then summarized to obtain coefficients which are dependent upon the climate of the area being analyzed. The data series are then reanalyzed using the derived coefficients to determine the amount of moisture required for normal weather during each month. The monthly departures from normal conditions are converted to indices of moisture anomaly. Finally, these indices are converted to the drought index. Note that while the index is routinely calculated on a monthly time scale, it can also be calculated for other time scales such as on a weekly basis.

Climatically appropriate precipitation P_c for any individual time scale such as a month is

$$P_c = a\mathrm{PE} + b\mathrm{PR} + c\mathrm{PRO} - d\mathrm{PL} \quad (1)$$

where, for the month, PE is potential evapotranspiration, R is potential recharge, PRO is potential runoff, and PL is potential loss. The coefficients are ratios of long-term mean quantities: a, evapotranspiration to potential evapotranspiration; b, recharge to potential recharge; c, runoff to potential runoff; and d, loss to potential loss. The difference between the observed precipitation in the month and P_c is the monthly moisture anomaly. The difference is multiplied by a standardizing factor that is designed to account for variations in climate at different sites, and the product is called the moisture anomaly index Z. The Palmer Drought Index PDI for month t is then calculated by

$$\mathrm{PDI} = .897\mathrm{PDI}_{t-1} + .333Z_t \quad (2)$$

This recursive equation was empirically determined by arbitrarily defining an extreme drought as having an index value of -4, finding, for the historically driest periods in both central Iowa and western Kansas, a relationship between the maximum observed monthly rates at which the negative values of Z accumulated during the observed dry intervals, and then determining the rate at which Z must increase in order to maintain a constant value of the PDI. The values of the coefficients show that a current month's PDI is comprised of only one-third of the current month's precipitation deficit and of almost nine-tenths of the previous month's PDI. In other words, the PDI for a given month contains a long-term memory of previous moisture conditions.

The PDI calculation requires both precipitation and temperature observations. The latter variable is used in the estimation of evapotranspiration.

In practice, separate indices are calculated for wet and dry spells. The final PDI is either the wet or dry index, and the decision is based on whether or not spells are incipient, established, or ended. The practical calculation illustrates the complexity of the PDI. Because of this complexity, it is not uncommon for a time series of the PDI to exhibit large, sudden changes.

STANDARDIZED PRECIPITATION INDEX (SPI)

The impacts of a water deficit are a complex function of water source and water use. The time scale over which precipitation deficits accumulate becomes extremely important and separates different types of drought. As described by McKee *et al.* (1993), some of the practical issues that are important in any analysis of drought are time scale, probability (the expected frequency of an event), and precipitation deficit.

Addressing these issues, they developed a standardized precipitation index (SPI), where the standardization is based on probability.

The SPI can be calculated for time scales that are important to the water analyst. Moving total time series are constructed from the observed precipitation data and then used for the SPI computation. For example, if the observed data consist of a time series of monthly precipitation amounts, and the analyst is interested in three-month events, then a new time series is constructed by summing the first three monthly amounts, then summing the amounts in months 2, 3 and 4, then summing the amounts in months 3, 4 and 5, etc. The 3-month SPI is then calculated from this new time series.

The first step in the calculation of the SPI is to determine a probability density function that describes the long-term series of observations. Once this distribution is determined, the cumulative probability of an observed precipitation amount is computed. The inverse normal (Gaussian) function is then applied to the probability. The result is the SPI.

SPI values are positive (negative) for greater (less) than median precipitation. The departure from zero is a probability indication of the severity of the wetness or aridity that can be used for risk assessment. The time series of the SPI can be used for drought monitoring by setting application-specific thresholds of the SPI for defining drought beginning and ending times. Accumulated values of the SPI can be used to analyze drought severity.

McKee *et al.* (1993) used a two parameter gamma density function to describe the precipitation observations for all time intervals at a site. Whether or not this distribution is an appropriate model of the observed precipitation data over various time intervals at sites throughout the U.S. is moot. As described in the next section, the PDI-SPI comparison described herein is based on SPI values calculated from a regional density function that differs from what McKee *et al.* (1993) used. Obviously, a uniform method of calculating the SPI would be desirable so that results from different investigators can be compared; collaborative studies are currently in progress to compare SPI values that are calculated from different density functions.

COMPARISON METHODOLOGY

The National Electronic Drought Atlas (Teqnical Services, 1997) contains the PDI for 1035 sites in the contiguous U.S. The record lengths vary among the sites, but were at least 60 years at all sites. The Atlas also contains probabilities of monthly, multimonthly, annual and multiyearly precipitation amounts. The probability densities were based on an index flood procedure (Kite, 1988) that resulted in regional growth curves for 111 homogeneous precipitation regions (Guttman, 1993; Guttman *et al.*, 1993). The same precipitation data that were used for the PDI computations were used for computing time series of moving total precipitation amounts spanning 1, 2, 3, 6, 12, 24 and 36 months. The probability of observing these running precipitation totals was then computed from the growth curves contained in the Atlas. These probabilities were then transformed into the SPI.

For each of the 111 regions, the site with the longest record length was selected for spectral analysis. This analysis technique is used to look for cyclical patterns in a time series. The time series is decomposed into a sum of sine and cosine waves of different amplitudes and wavelengths. The amplitude of a given wave or cycle, when smoothed over the whole duration of the time series, is an estimate of the contribution or importance of the cycle to the observed time series. Spectral densities of the PDI time series and the 1-, 2-, 3-, 6-, 12-, 24- and 36-month SPI time series were computed. The higher the density, the more a given cycle contributes to the observed time series. Cross spectral analysis, which is similar to spectral analysis but looks at the interrelationships between two time series, was also performed. Cross spectral densities between the PDI time series and each of the SPI time series were computed. The aim of these analyses was to gain an understanding of the underlying structure of both the PDI and the SPI as well as to gain insight into the spatial consistency of the indices.

The data were processed through the SAS (1988) spectral analysis software. Using the finite Fourier transform, the spectral analysis procedure decomposes the time series into a sum of sine and cosine waves of different amplitudes and wavelengths. The decomposition is then smoothed by a weighted moving average (spectral window) to produce an estimate of the spectral density of the series. Following Priestley (1981), a Hanning spectral window with a bandwidth equal to about twice the cube root of the number of data values in the time series was used. This window and bandwidth were chosen in order to differentiate between two cycles with slightly different wavelengths. Cross spectra were also computed using the SAS spectral software.

RESULTS

The PDI spectra for the 111 sites all exhibit a general pattern of densities that do not decrease as the period increases. A more detailed examination of the PDI spectra indicates, however, that there appear to be eight distinct characteristic spectra. Each type is illustrated in Figure 1, and a description and interpretation of each type follows.

The first type is a continuously increasing spectral density as the period increases. This type indicates a memory inherent in the PDI that lasts for at least nine years. In other words, a current month's PDI is influenced by the PDI for each month for at least the previous nine years (108 months). Types 2-5 are similar to type 1 in that the densities increase with increasing period, but differ from type 1 in that after a threshold period, the densities are approximately constant. The threshold density indicates the limit of the previous months' influence (memory) on a current month's PDI. The memory ranges from about 2.5 years for type 2 to 3.5 years for type 3 to 5 years for type 4 to 6 or 7 years for type 5. Types 6 and 7 also show increasing spectral density with increasing period, but the increase is halted by level density corresponding to periods of about 2 to 4 years for type 6

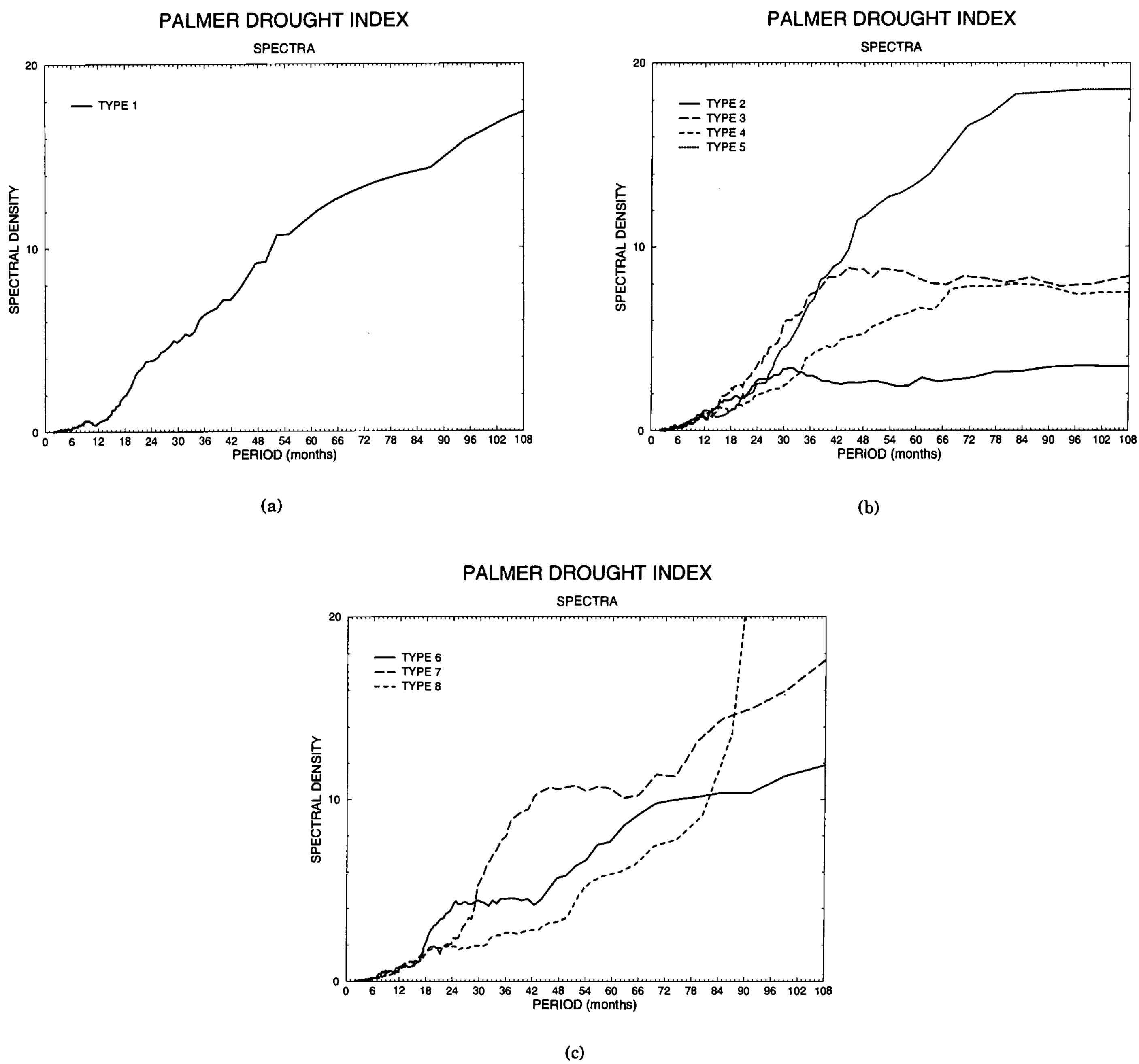

Figure 1. Example of PDI Spectra: (a) Type 1; (b) Types 2, 3, 4, and 5; and (c) Types 6, 7, and 8.

and 4 to 6 years for type 7. Type 6 spectra suggest that a current month's PDI is influenced by the PDI for the previous two years and previous 4 to 6 years, but not for the previous 2 to 4 years. Similarly, type 7 spectra suggest that current month's PDI is influenced by the PDI for the previous four years and more than the previous six years, but not the PDI for the previous four to six years. The last characteristic spectra has relatively low density for periods up to about seven or eight years and then high density for longer periods suggesting that the PDI for a current month is highly related to the PDIs of more than seven or eight years earlier.

The spatial distribution of the eight types of PDI spectra is shown in Figure 2. Except in a few small areas of the U.S., there does not appear to be any spatially coherent patterns in the PDI spectra; i.e., the spectral patterns vary from site to site.

Summarizing the PDI spectra, all eight types indicate that a current month's PDI is dependent upon previous month's PDI. The duration of the dependence is what separates the first five types, ranging from the previous 2.5 years (type 2) to more than nine years (type 1). For the last three types, the influence of antecedent conditions on a current month's PDI appears to be cyclical in that there are years of high influence followed by years of low influence once again followed by years of high influence. These last three types may be indicative of climatic quasi-periodic events such as El Niño affecting the site.

The SPI spectra are illustrated in Figure 3. For each spectrum there is a very low spectral density up to a threshold period, then a rise, and then a levelling off. The threshold is the same period as the time scale of the SPI (two months for the 2-month SPI, three months for the 3-month SPI, etc.) and represents the duration n for which the observed monthly precipitation totals are summed to obtain the time series for computing the n-month SPI. Unlike the PDI spectra, the SPI spectra exhibit the same pattern at all locations.

Cross spectra between the PDI and each of the SPI indices were also computed to show the similarities and differences between the two indices. Phase diagrams (Figure 4), which show the difference in timing when peaks and troughs of a given cycle of the PDI and SPI pass a site, are similar at all locations. The diagrams show that peaks in oscillations in the 1-, 2-, 3- and 6-month SPI progressively lead (phase > 0) those in the PDI. Peaks in the 24-and 36-month SPI

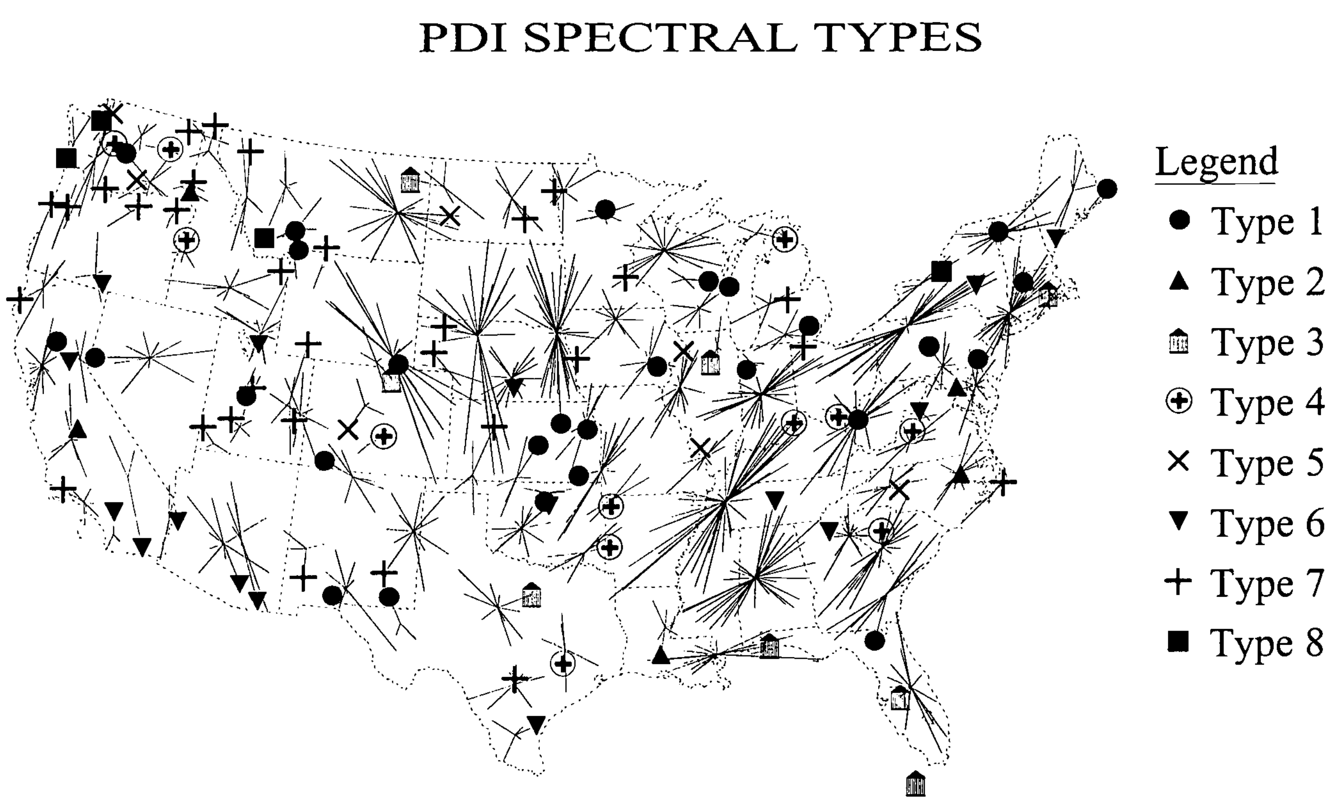

Figure 2. Spatial Distribution of PDI Spectral Types. Background lines point from the centroid of a quasi-homogeneous region to the location of sites in the region.

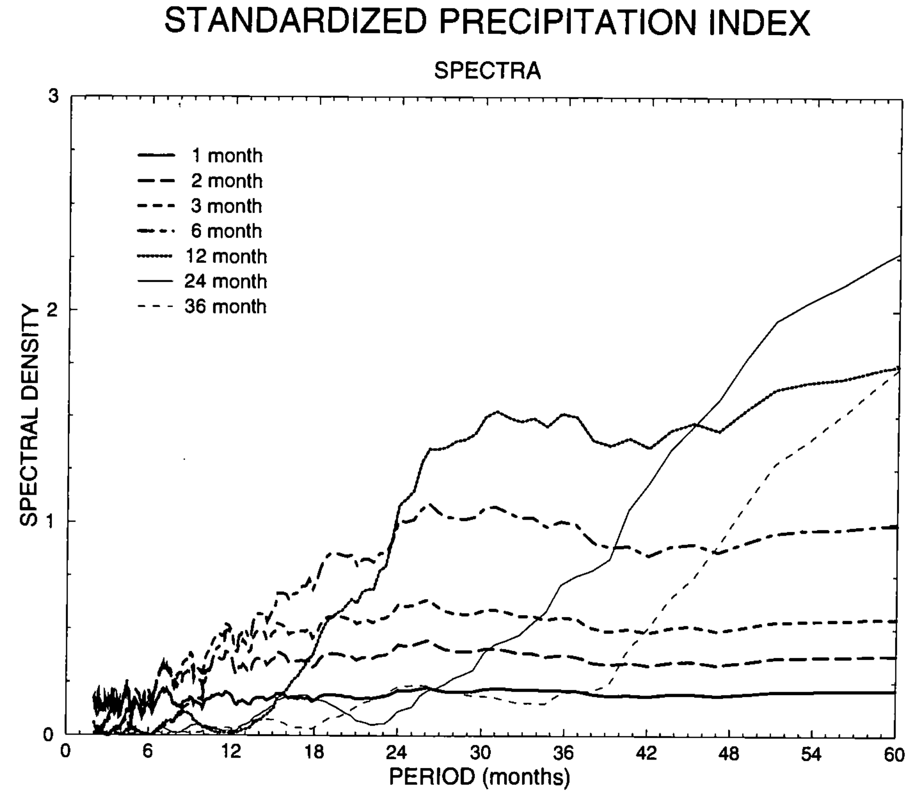

Figure 3. Example of SPI Spectra for Durations of 1 to 36 Months.

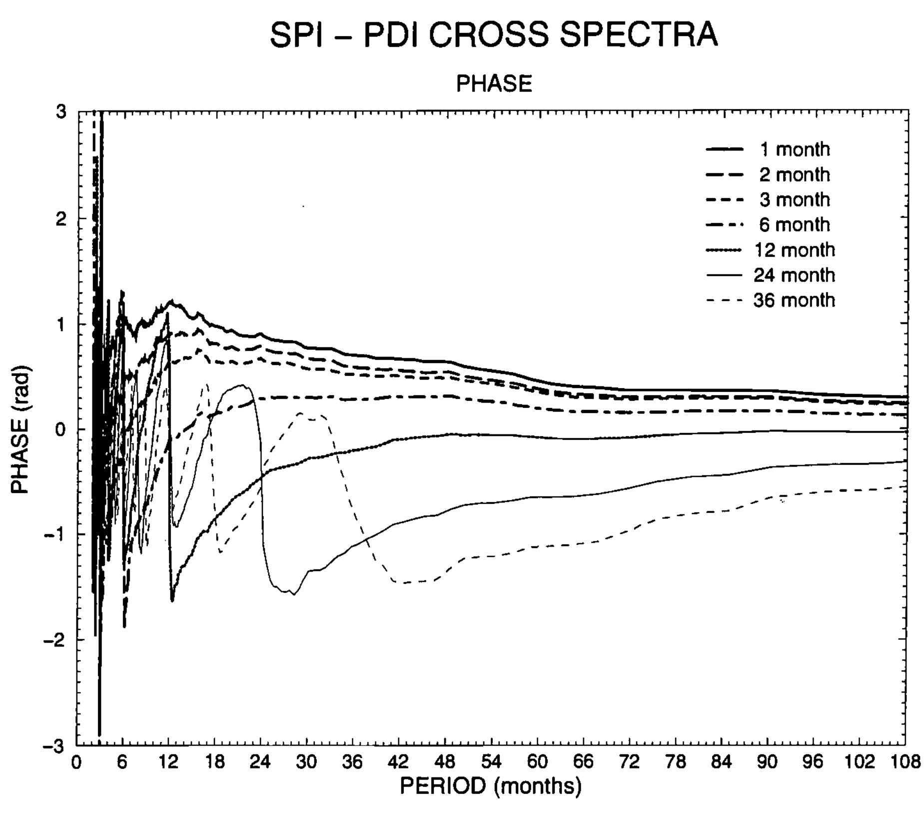

Figure 4. Example of the Cross Spectra Phase Between the SPI and PDI for SPI Durations of 1 to 36.

oscillations lag (phase < 0) those in the PDI. The 12-month SPI oscillations occur almost simultaneously (phase = 0) with those in the PDI. Note that in Figure 4, the oscillations in the plots for periods less than the time scale of the SPI result from computational noise and should be ignored.

Coherence, which can vary between 0 and 1, measures the correlation between two time series at a specified frequency. Examples of the highest and lowest coherence patterns are shown in Figures 5 and 6. As with the phase plots in Figure 4, the oscillations in the coherency for periods less than the time scale of the SPI result from computational noise and should be ignored. The coherence between the 1- through 12-month SPI and the PDI is high at almost all locations and is generally not frequency dependent. The coherence between the PDI and the 24- and 36-month SPI is relatively low compared to the shorter time scales, but is still high in magnitude and also not frequency dependent. The coherency figures can be interpreted to mean that the PDI and SPI are highly and linearly related.

DISCUSSION

The PDI is, by definition (Equation 2), an autoregressive process of first order. This type of process means that a PDI for a month is linearly related to the PDI for the previous month. The general spectral pattern of the PDI (Figure 1) reflects an autoregressive process, but the inherent memory of the PDI is longer than would be expected from a first order process (one month). The long-term memory, which is on the order of years, results from the nature of the water balance accounting approach upon which the index is based. A current month's contribution to the PDI is highly dependent on antecedent soil and atmospheric moisture conditions, and the temporal impact of these antecedent conditions is not only long-term, but also could be highly variable. The calculation of the PDI is complex, and this complexity leads to difficulty in interpreting exactly what the index is representing in the physical world.

The SPI for durations that are longer than a month (the basic time period of measurement) is by definition a moving average process, and the spectral patterns reflect this type of process (Figure 3). The SPI describes the behavior of only one variable, precipitation, and is easy to interpret in a probabilistic sense.

High coherence between the PDI and SPI (Figures 5 and 6) indicate that precipitation is the dominant factor in the PDI. The phase relationships between the two indices (Figure 4) show that for periods of less than about a year, the PDI lags the SPI, and for periods of about a year, the two indices are in phase.

Spatial comparison of the spectra show a consistent shape for the SPI, but several different shapes for the PDI (Figure 2). The interpretation of the SPI can therefore be considered to be the same at all locations. The lack of spatial consistency of the PDI means that the index is likely not representing similar characteristics at all locations and therefore should not be used to compare conditions at different locations.

The SPI is recommended as a drought index because it is simple, spatially consistent (invariant) in its interpretation, probabilistic so that it can be used in risk and decision analyses, and can be tailored to time periods of a user's interest (e.g., three months for the life cycle of a crop, or several years for water storage). The PDI, on the other hand, is very complex, spatially variant, difficult to interpret, and temporally fixed.

Acceptance by the user community of the SPI will, however, have to wait until agreement is reached on probability distributions and models that should be fit to the precipitation data. Until agreement is reached, index values corresponding to a given precipitation amount may vary depending on the fits to the data. Further research is needed to assess the robustness of the models as well as the impact of different distributions on the SPI. Once agreement is reached, the index will be able to be computed by any analyst, and all analysts will be computing the index according to the same methodology.

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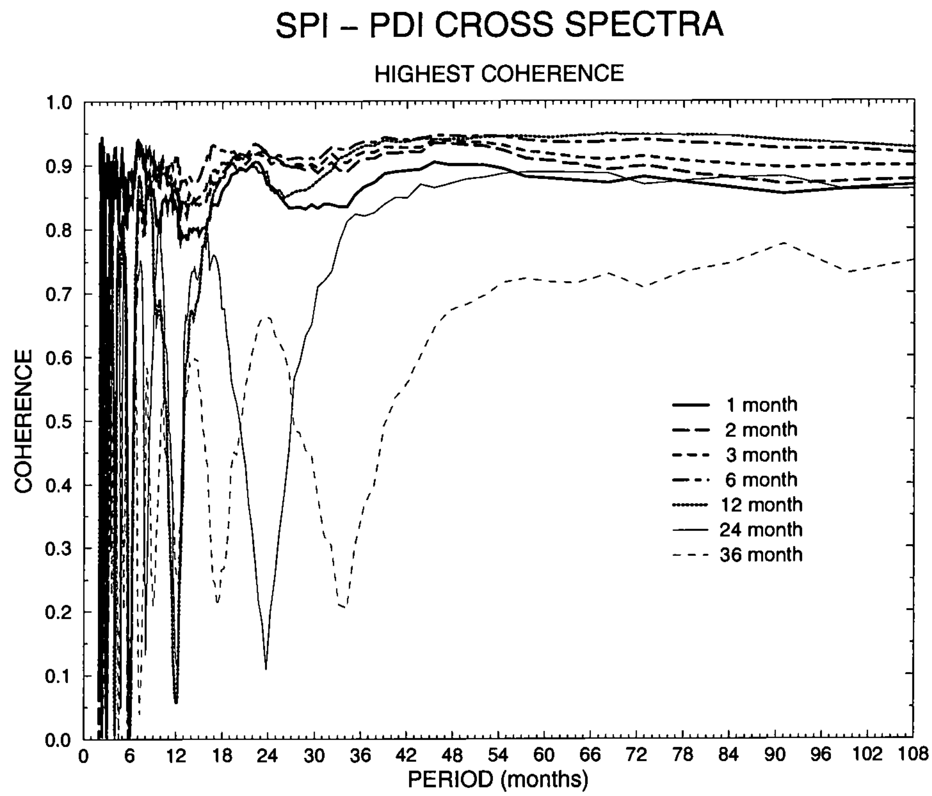

Figure 5. Example of the Cross Spectra High Coherence Between the SPI and PDI for SPI Durations of 1 to 36 Months.

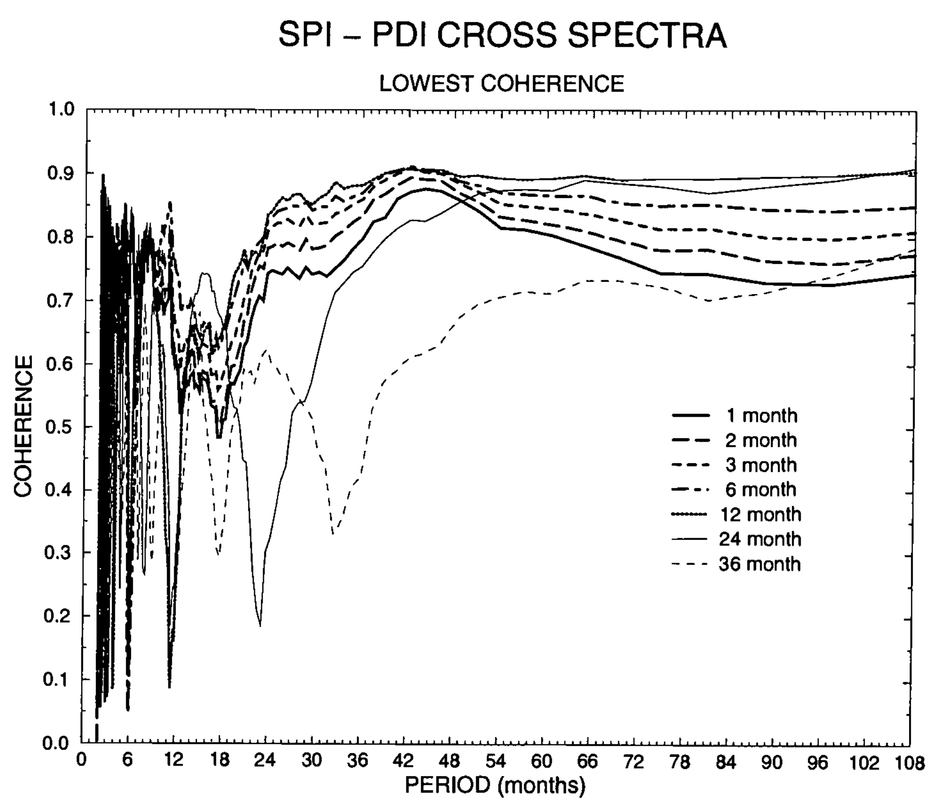

Figure 6. Example of the Cross Spectra Low Coherence Between the SPI and PDI for SPI Durations of 1 to 36 Months.

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